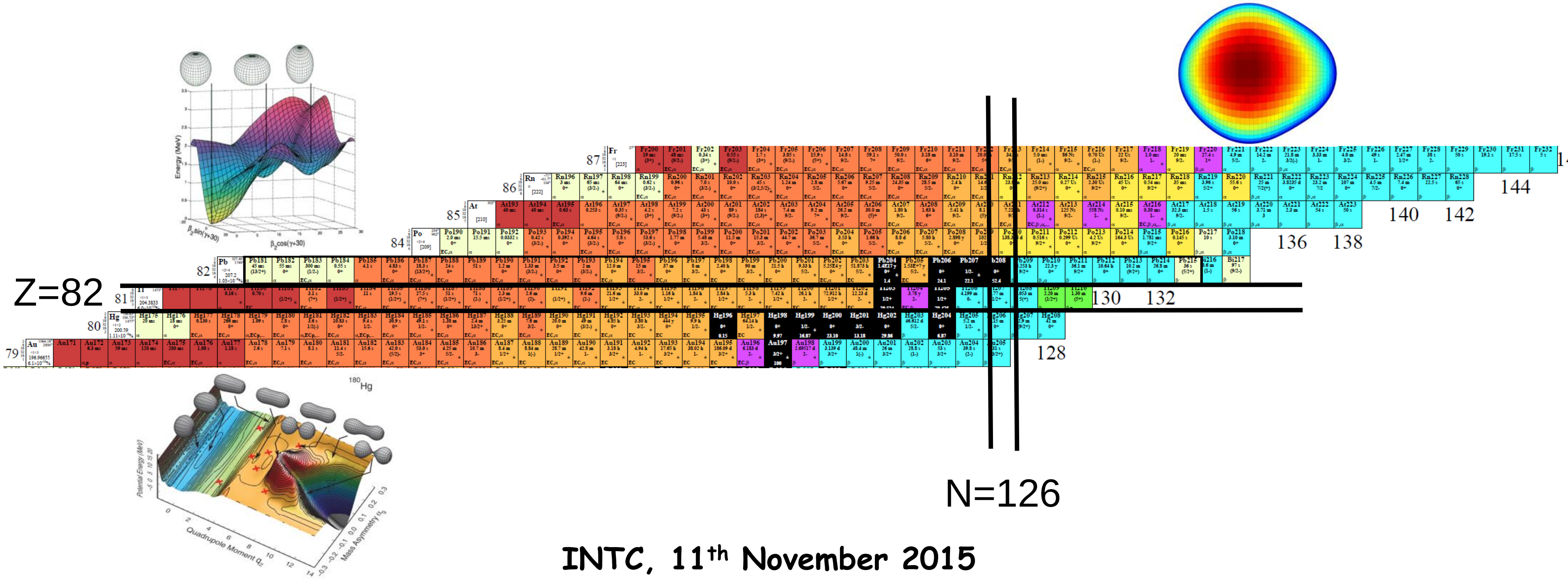
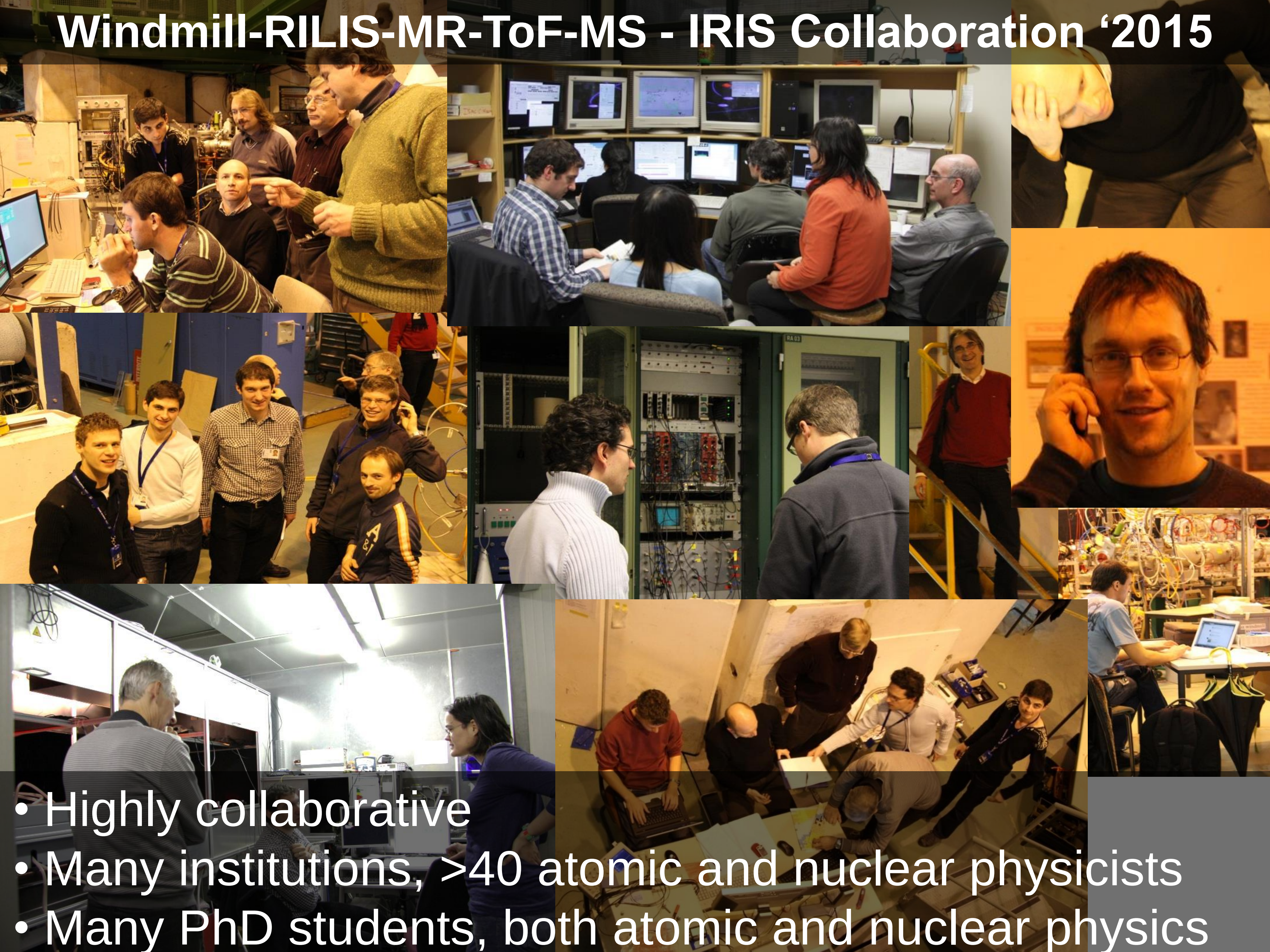
Charge radii measurements in the bismuth chain and beta-delayed fission of ^{188m1,m2}Bi

Andrei Andreyev
University of York, UK and JAEA, Tokai, Japan
on behalf of the Windmill Collaboration



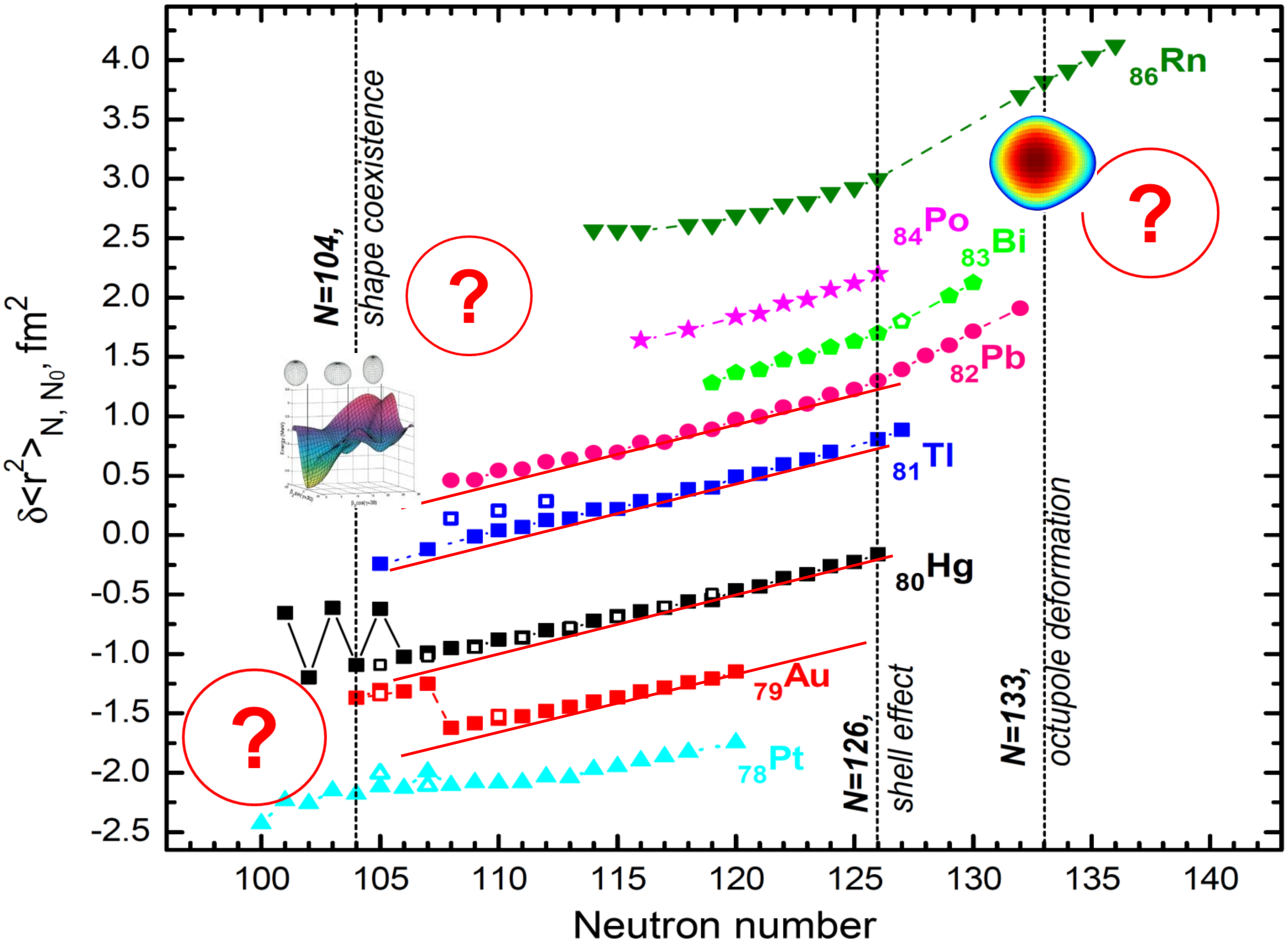
INTC, 11th November 2015

Windmill-RILIS-MR-ToF-MS - IRIS Collaboration ‘2015



- Highly collaborative
- Many institutions, >40 atomic and nuclear physicists
- Many PhD students, both atomic and nuclear physics

Pre-2003: Charge Radii in the Lead Region



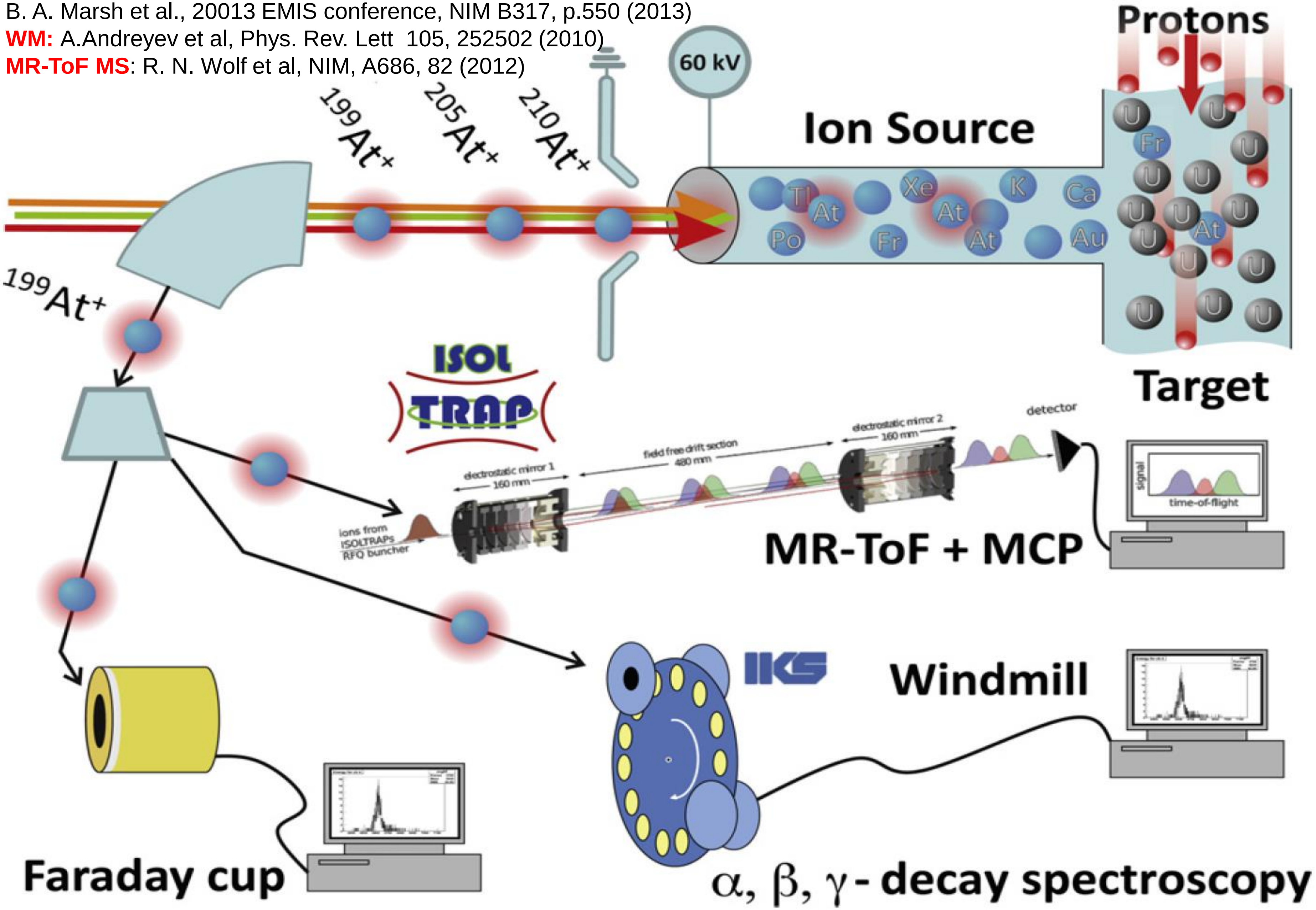
- Shape coexistence around N~104
- Sphericity around N=126, kink in radii, high-spin isomers
- Octupole effects around N~132, inverse odd-even radii staggering

Our tools '2015: WindMill (WM), FC, MR-TOF MS

B. A. Marsh et al., 20013 EMIS conference, NIM B317, p.550 (2013)

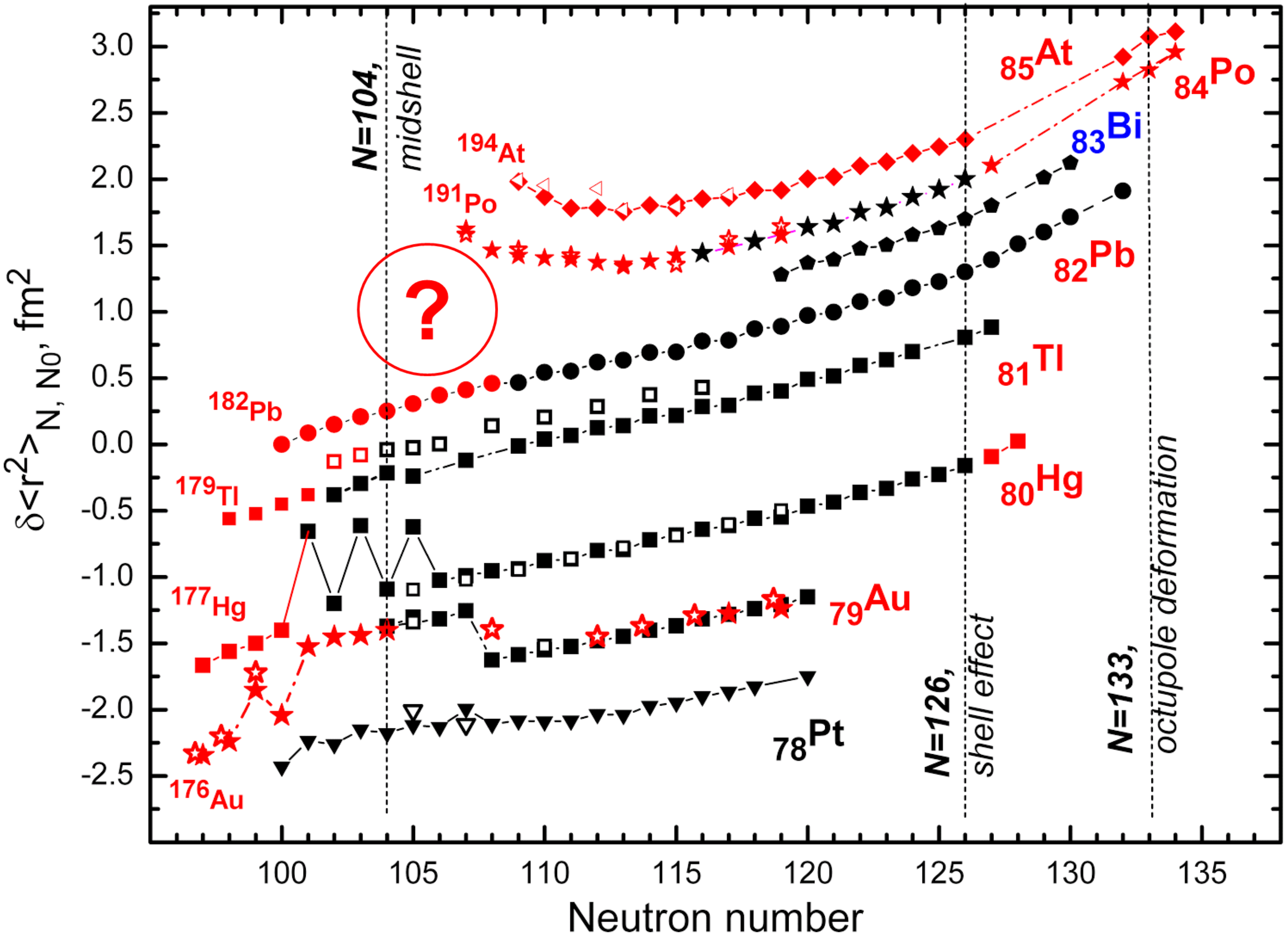
WM: A.Andreyev et al, Phys. Rev. Lett 105, 252502 (2010)

MR-ToF MS: R. N. Wolf et al, NIM, A686, 82 (2012)



Status 2015: WM-RILIS-MR-TOF MS+IRIS

- IS/HFS for >70 isotopes (and isomers) for Au,Hg,Tl,Pb,Bi,Po,At
- Beta-delayed fission in Tl and At (Fr)
- Huge amount of ‘by-product’ nuclear structure information



7 PhD theses

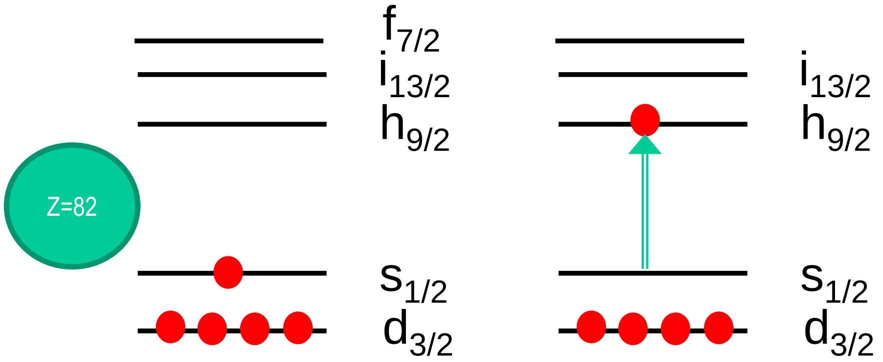
'Reciprocity' of Tl and Bi relative to Pb(Z=82)?

(scaling law for *oblate* intruders in Tl,Pb,Bi)

Odd-A Tl (Z=81)

I^{π}=1/2^{+} (spherical g.s, 0p-1h)

I^{π}=9/2^{-} ('oblate' intruder, 1p-2h)

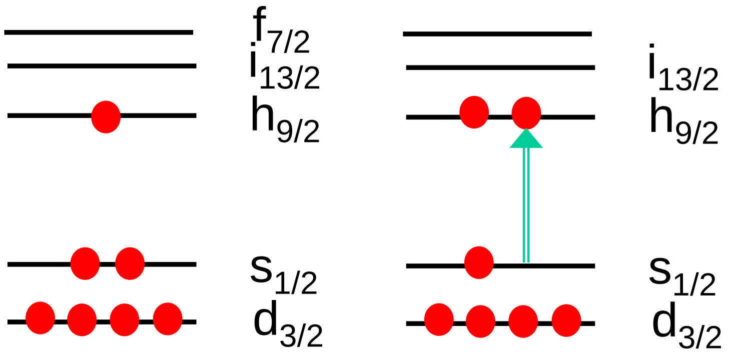


Odd-A Bi (Z=83)

I^{π}=9/2^{-} (spherical g.s, 1p-0h)

I^{π}=1/2^{+} ('oblate' intruder, 2p-1h)

I^{π}=1/2^{+} ('prolate' intruder, 2p-1h)



- **"Scaling law" for *oblate* intruders in Tl, Pb,Bi – if the same number of valence protons, then:** $E^*(9/2^-,\mathrm{Tl}) \approx E^*(1/2^+,\mathrm{Bi}) \approx 1/2E^*(0^+,\mathrm{Pb})$
- **Parabolic trend as a function of N**

- However, 'strange' 1/2^{+} intruder in ^{189}Bi? (also in ^{187}Bi, see next slide) – prolate?

M.Huyse et al, PLB201,293(1988)

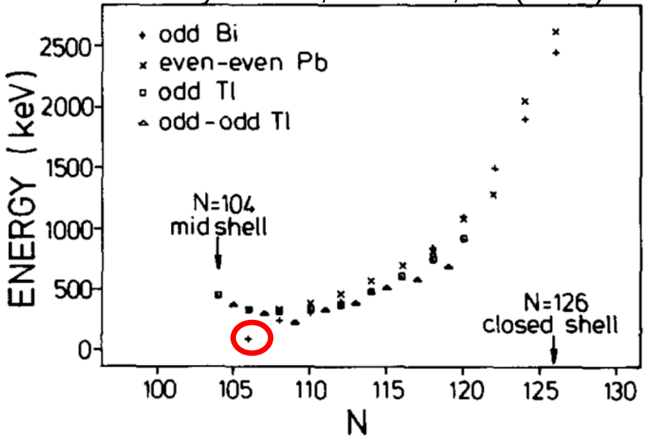
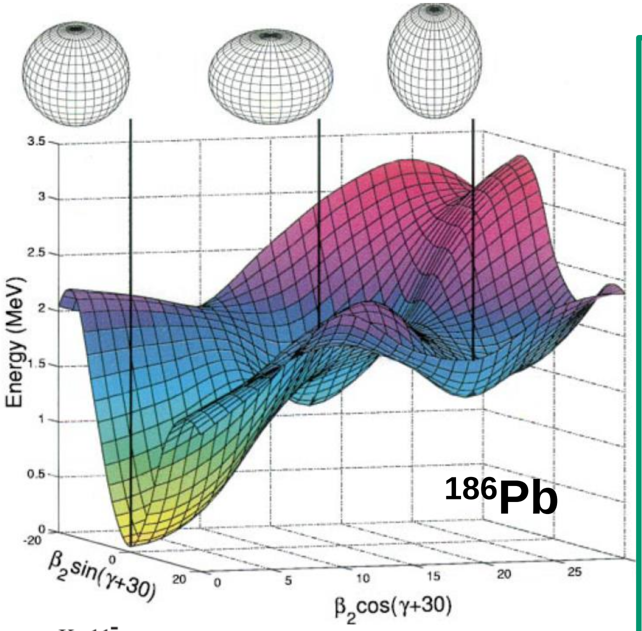
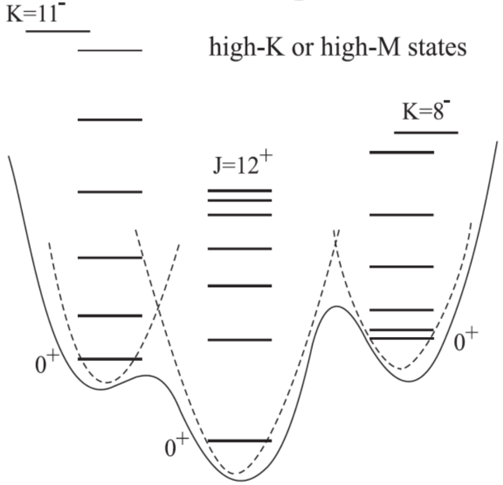


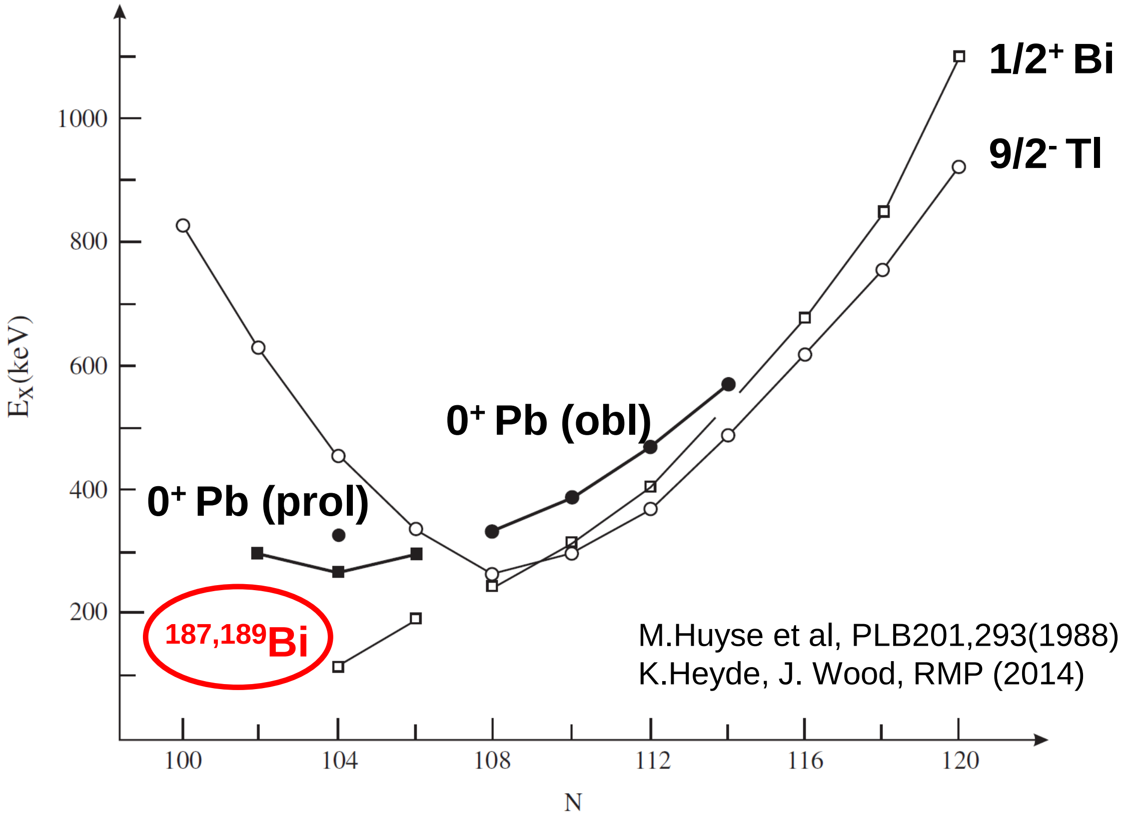
Fig. 4. Systematics of the intruder-state excitation energies. The excitation energy of the 0^{+} intruder states in the even–even Pb nuclei is divided by two. References to other work can be found

Bi's as a Pb core + a proton?

(or, what happens in, e.g. ^{187}Bi if one couples a proton to states in ^{186}Pb?)







M.Huyse et al, PLB201,293(1988)
K.Heyde, J. Wood, RMP (2014)

FIG. 17. Systematics of the odd-Tl π(1p-2h), odd-Bi π(2p-1h), and even-Pb π(2p-2h) intruder-state energies (the even-Pb energies are divided by 2). Note the strong correlation of the three quantities:

- Unexpected deviation of E*(1/2⁺) from an 'oblate parabolic' rule in ^{187,189}Bi
- Coupling to prolate? – should be seen in radii/moments?

Shape Coexistence in Bi isotopes (selected states)

PHYSICAL REVIEW C **69**, 054308 (2004)

Shape-changing particle decays of ^{185}Bi and structure of the lightest odd-mass Bi isotopes

A. N. Andreyev,[1,*] D. Ackermann,[2,3] F. P. Heßberger,[2]
K. Heyde,[4] S. Hofmann,[2,5] M. Huyse,[6] D. Karlgren,[7] I. Kojouharov,[2] B. Kindler,[2] B. Lommel,[2] G. Münzenberg,[2,3]
R D. Page,[1] K. Van de Vel,[6,†] P. Van Duppen,[6] W. B. Walters,[8] and R. Wyss[7]

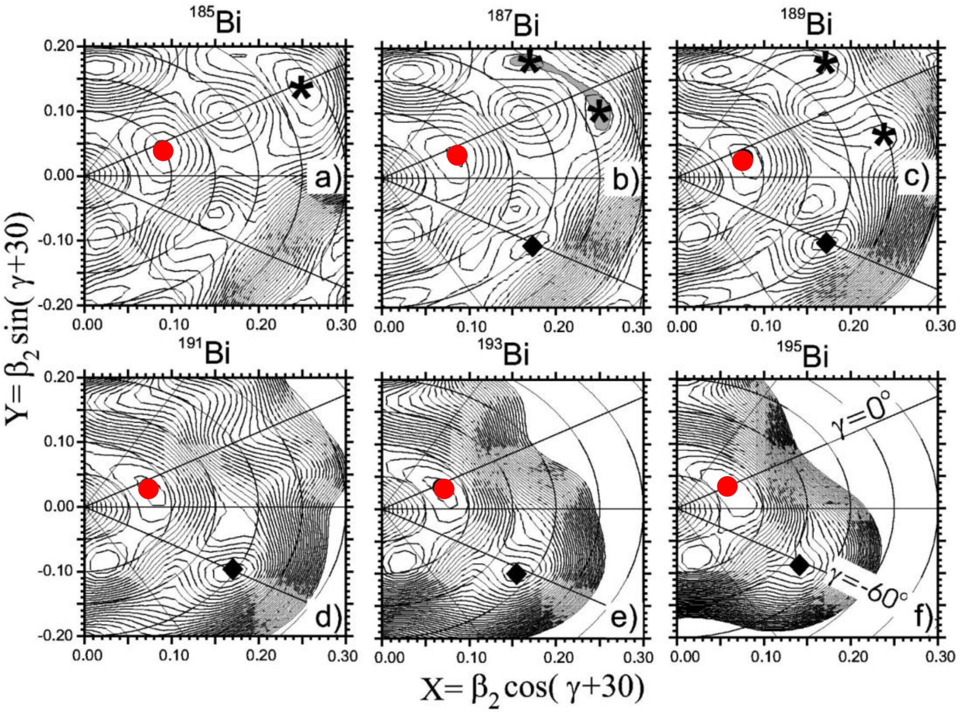
Negative parity states

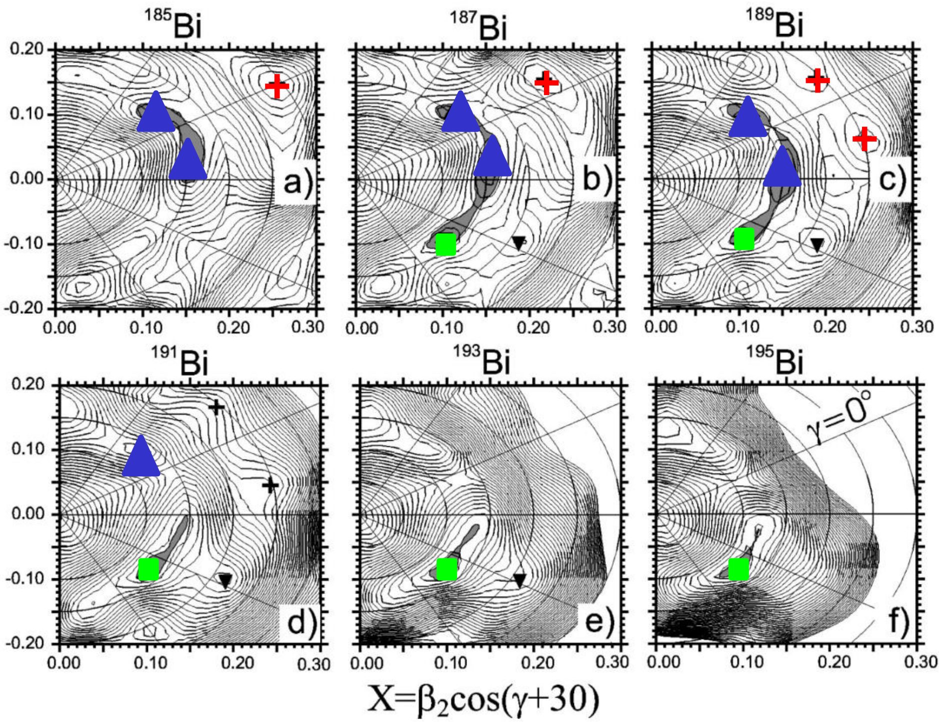
● 'Spherical' I^{π}(gs)=9/2$^-$

Positive parity states

🟩 'Oblate' intruder I^{π}=1/2$^+$

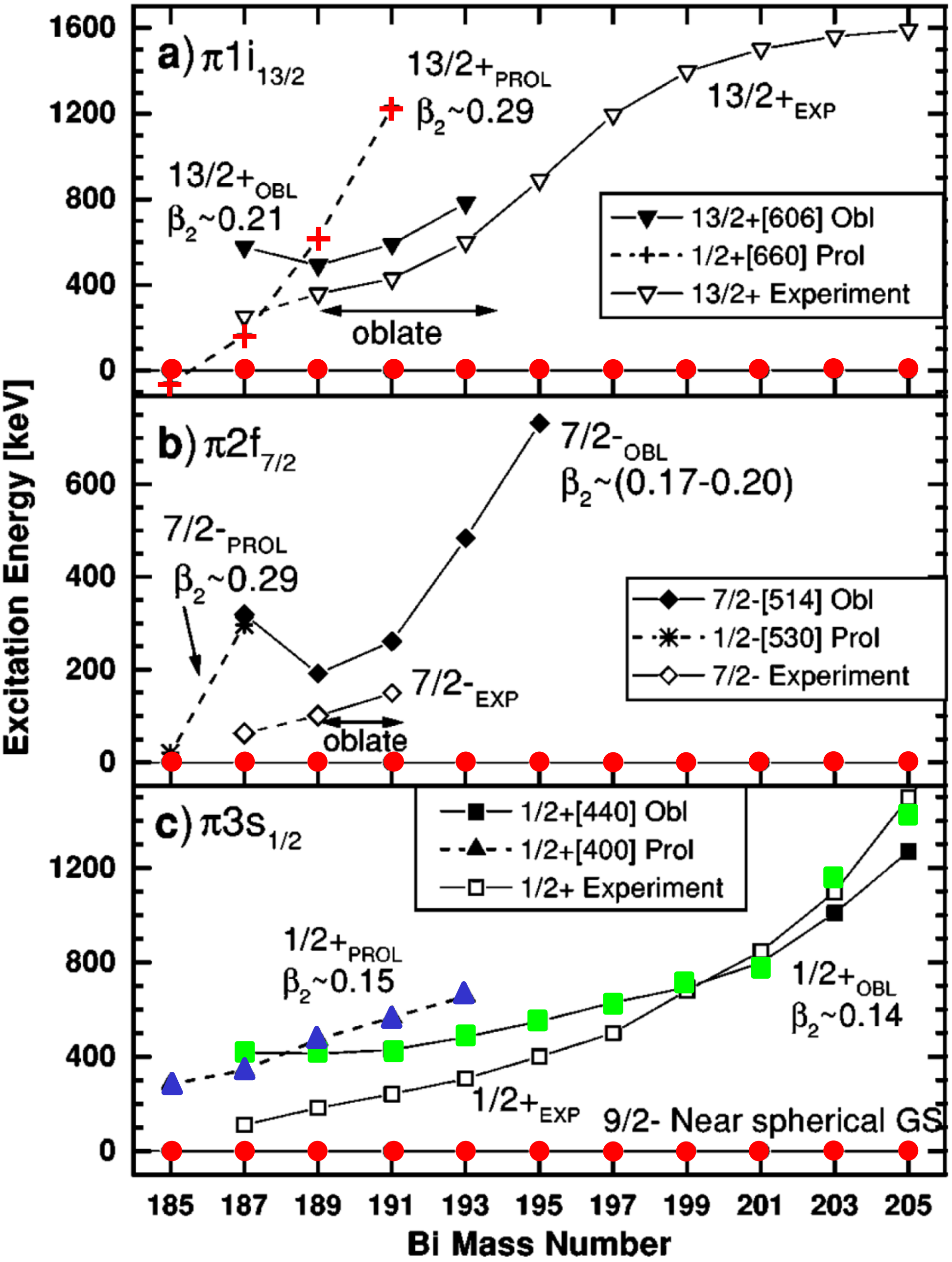
▲, + 'Prolate' intruders I^{π}=1/2$^+$



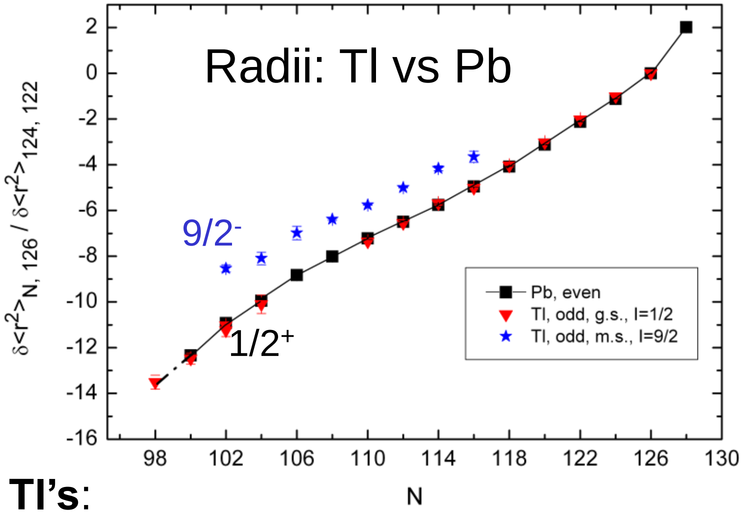


PES/PPR calculations predict an oblate intruder for heavier odd-A Bi's and low-energy coexistence of *several* 1/2$^+$ (oblate-prolate) states in the lightest Bi's

Coexistence in Bi isotopes due to $s_{1/2}$,$f_{7/2}$ and $i_{13/2}$ protons

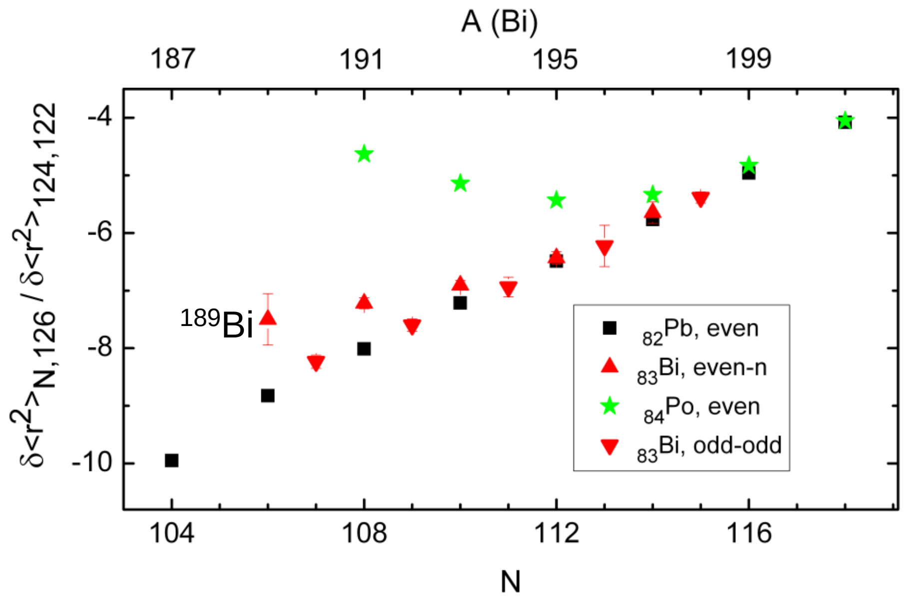


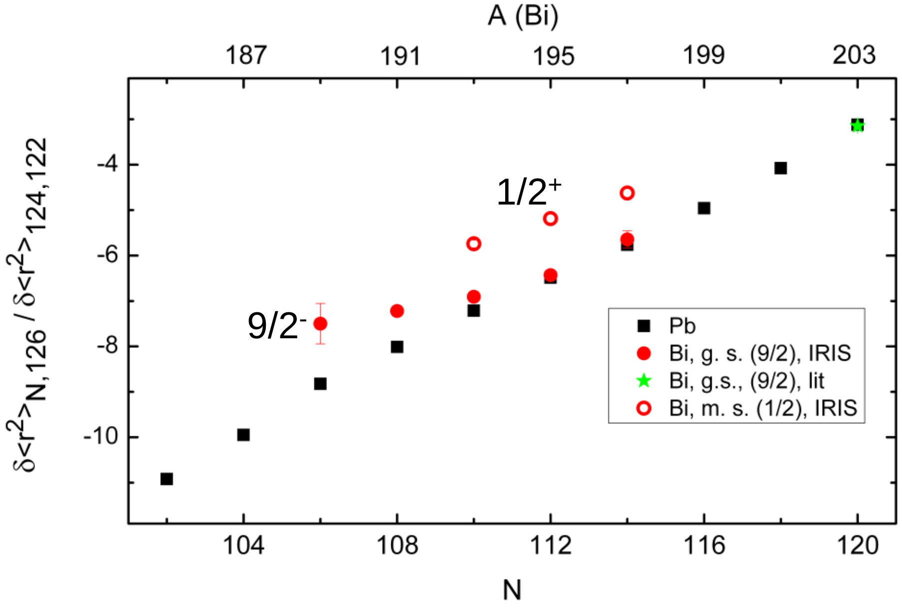
Tl-Pb-Bi radii comparison



Tl's:

- $1/2^+$ g.s. follow spherical 0^+ g.s. in Pb's
- $9/2^-$ is deformed, with nearly constant trend

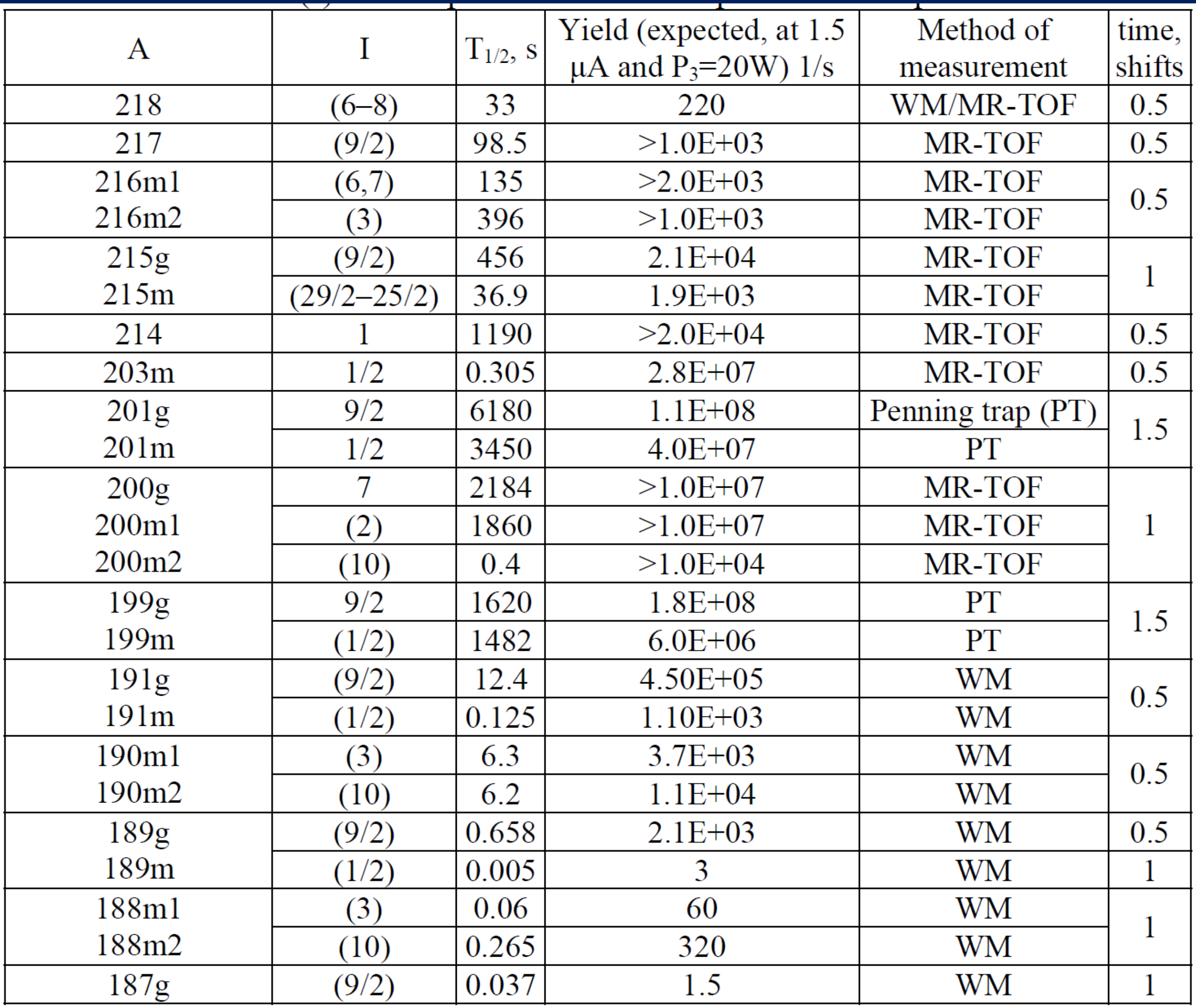




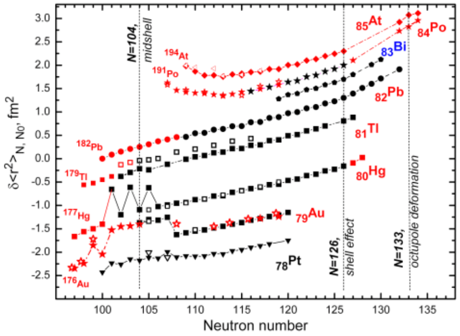
Bi's (preliminary IRIS data – red symbols):

- $9/2^-$ starts to deviate from spherical 0^+ g.s. in Pb's. **Need ^{187}Bi (and more precise ^{189}Bi)**
- $1/2^+$ is deformed in ^{193,195,197}Bi, with a nearly constant trend, **need data for light ^{189,191}Bi and for A(Bi)>197**

Planned HFS/IS measurements



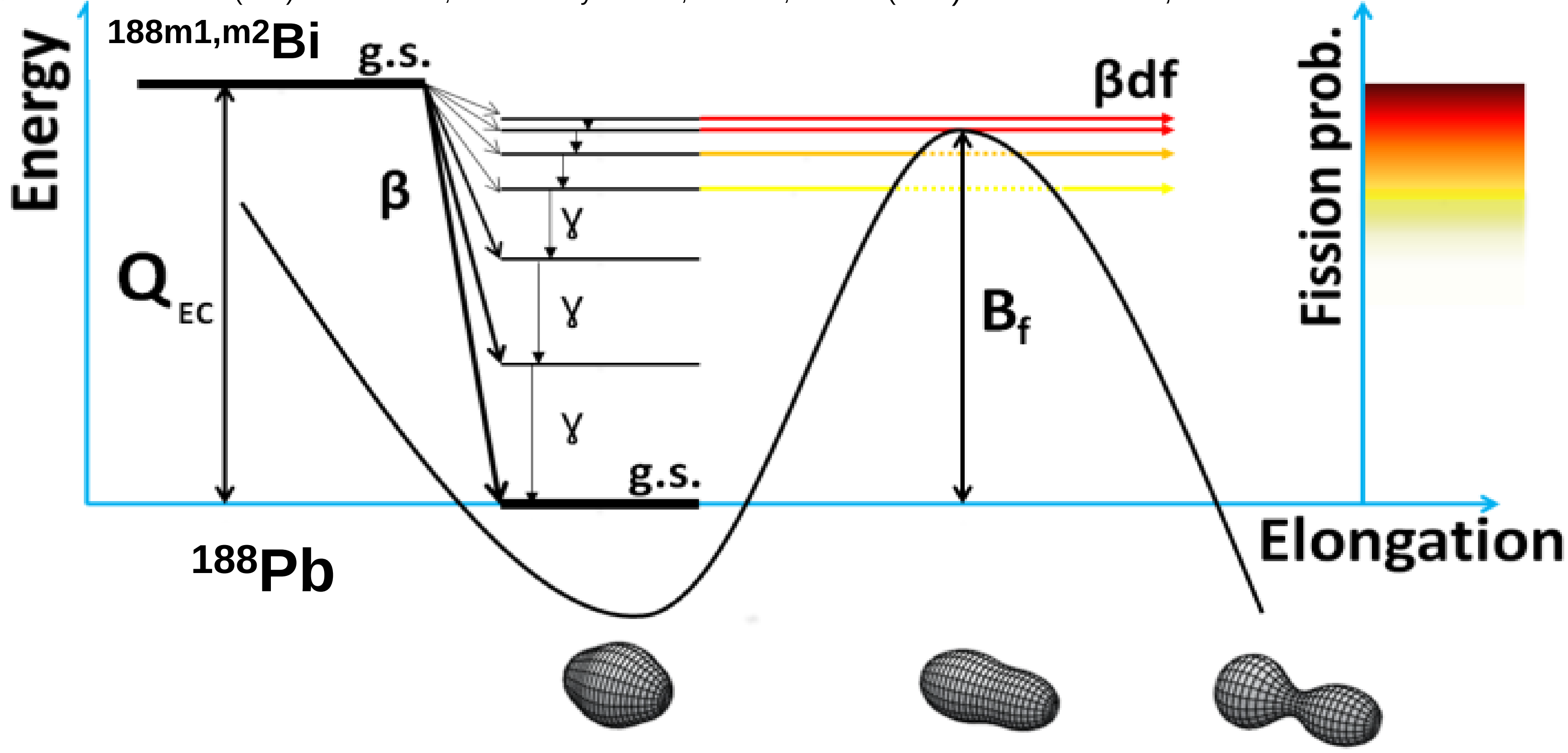
A	I	$T_{1/2}$, s	Yield (expected, at 1.5 μA and P_3=20W) 1/s	Method of measurement	time, shifts
218	(6–8)	33	220	WM/MR-TOF	0.5
217	(9/2)	98.5	>1.0E+03	MR-TOF	0.5
216m1	(6,7)	135	>2.0E+03	MR-TOF	0.5
216m2	(3)	396	>1.0E+03	MR-TOF	
215g	(9/2)	456	2.1E+04	MR-TOF	1
215m	(29/2–25/2)	36.9	1.9E+03	MR-TOF	
214	1	1190	>2.0E+04	MR-TOF	0.5
203m	1/2	0.305	2.8E+07	MR-TOF	0.5
201g	9/2	6180	1.1E+08	Penning trap (PT)	1.5
201m	1/2	3450	4.0E+07	PT	
200g	7	2184	>1.0E+07	MR-TOF	1
200m1	(2)	1860	>1.0E+07	MR-TOF	
200m2	(10)	0.4	>1.0E+04	MR-TOF	
199g	9/2	1620	1.8E+08	PT	1.5
199m	(1/2)	1482	6.0E+06	PT	
191g	(9/2)	12.4	4.50E+05	WM	0.5
191m	(1/2)	0.125	1.10E+03	WM	
190m1	(3)	6.3	3.7E+03	WM	0.5
190m2	(10)	6.2	1.1E+04	WM	
189g	(9/2)	0.658	2.1E+03	WM	0.5
189m	(1/2)	0.005	3	WM	1
188m1	(3)	0.06	60	WM	1
188m2	(10)	0.265	320	WM	
187g	(9/2)	0.037	1.5	WM	1



13 Shifts Requested for HFS/IS measurements

β-Delayed Fission of isomerically-pure beams of ^{188m1,m2}Bi

βDF of $^{186.188}$Bi: SHIP(GSI). J.F.W. Lane, A.N. Andreyev et al., PRC **87**, 014318 (2013) – identification, but no FFs mass measurement, no $P_{\beta DF}$



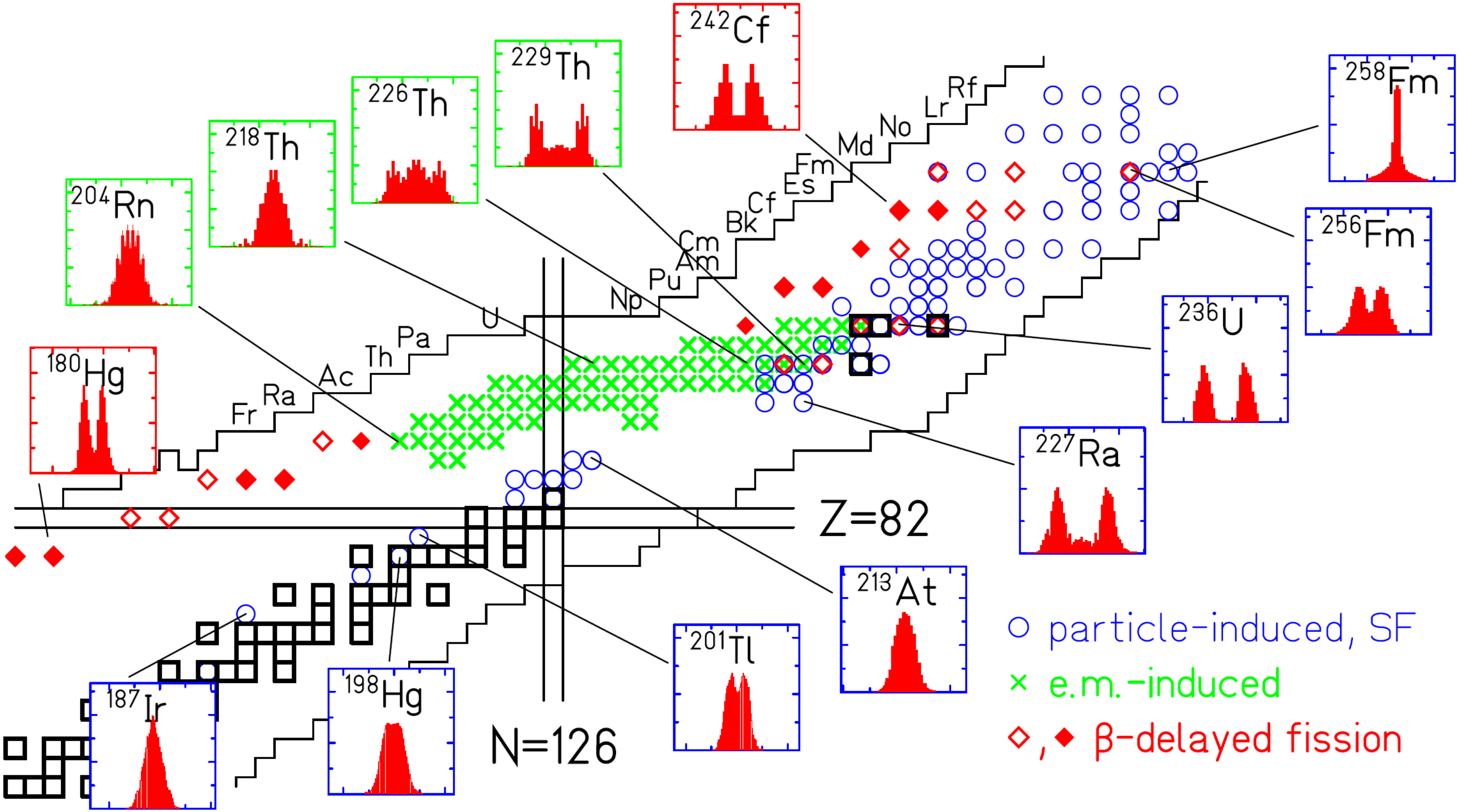
- •Two step process: β decay of precursor followed by fission of excited daughter
- •Low-energy fission (E* limited by Q_{EC}), e.g. Q_{EC}(^{188}Bi)=10.8 MeV, B_f(^{188}Pb)=10.3 MeV
- •Relatively low angular momentum of the precursor state

  e.g. ^{188}Bi: I=3 ($\pi h_{9/2} \times \nu p_{3/2}$) or I=10 ($\pi h_{9/2} \times \nu i_{13/2}$)

The goals: Studies of energy/mass distribution for fission fragments, TKE as a function of spin of the fissionning state in ^{188}Pb (as two different states are supposed to be populated via β decay of ^{188m1,m2}Bi)

IS466/IS534: Mapping 'Terra Incognita' in Low-Energy Fission
Beta-delayed fission of ^{178,180}Tl, ^{194,196}At, ^{200,202}Fr

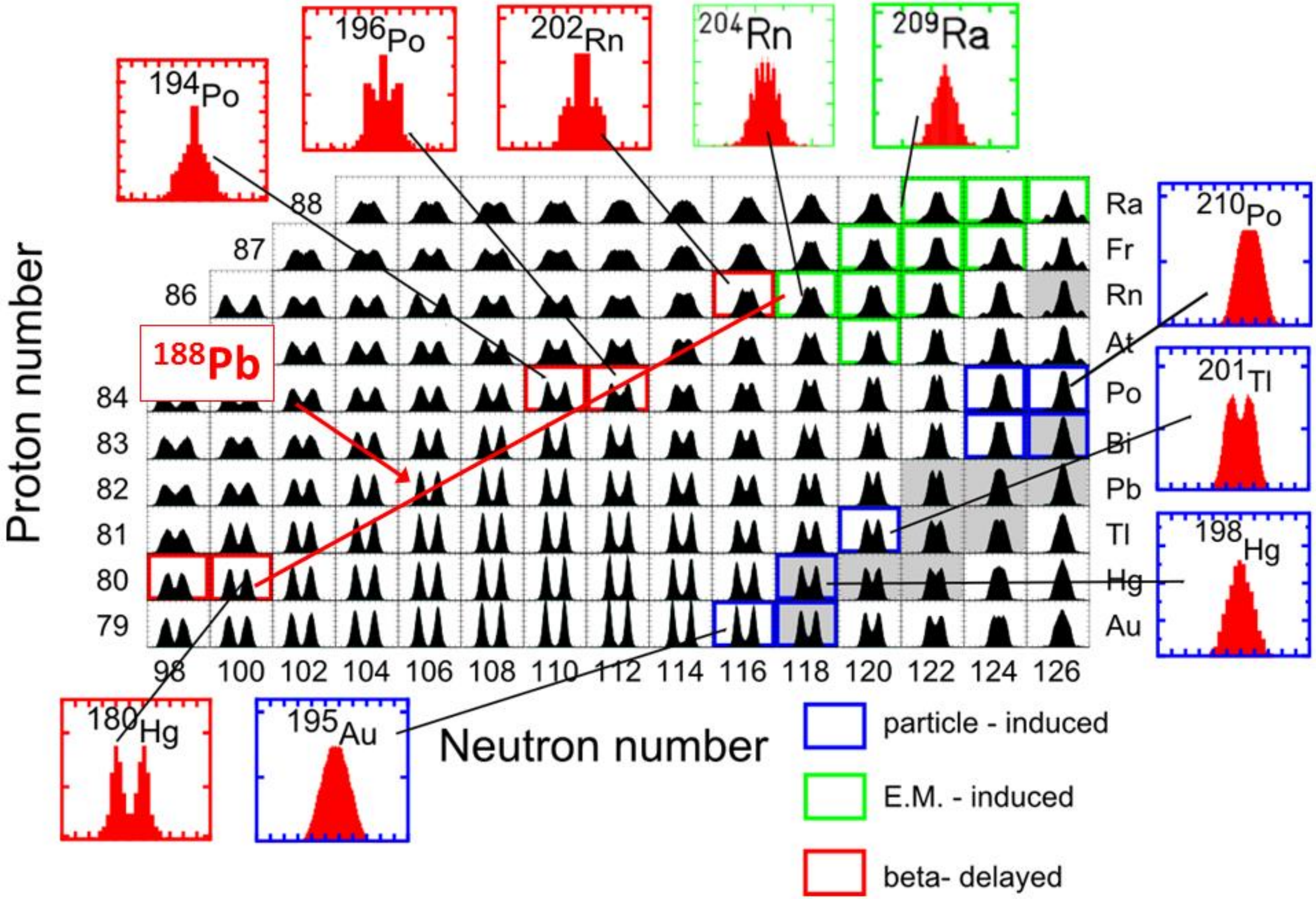
A.N. Andreyev, M. Huyse, P. Van Duppen, "Beta-delayed Fission", Reviews of Modern Physics, 85, 1541 (2013)



- 3 PhD thesis completed (UWS 2014, Leuven 2015, York 2015) Rev. Mod. Phys., PRL, 4 PRC's

Fission mass asymmetry of ^{188}Pb via βDF of isomerically-pure ^{188m1,m2}Bi

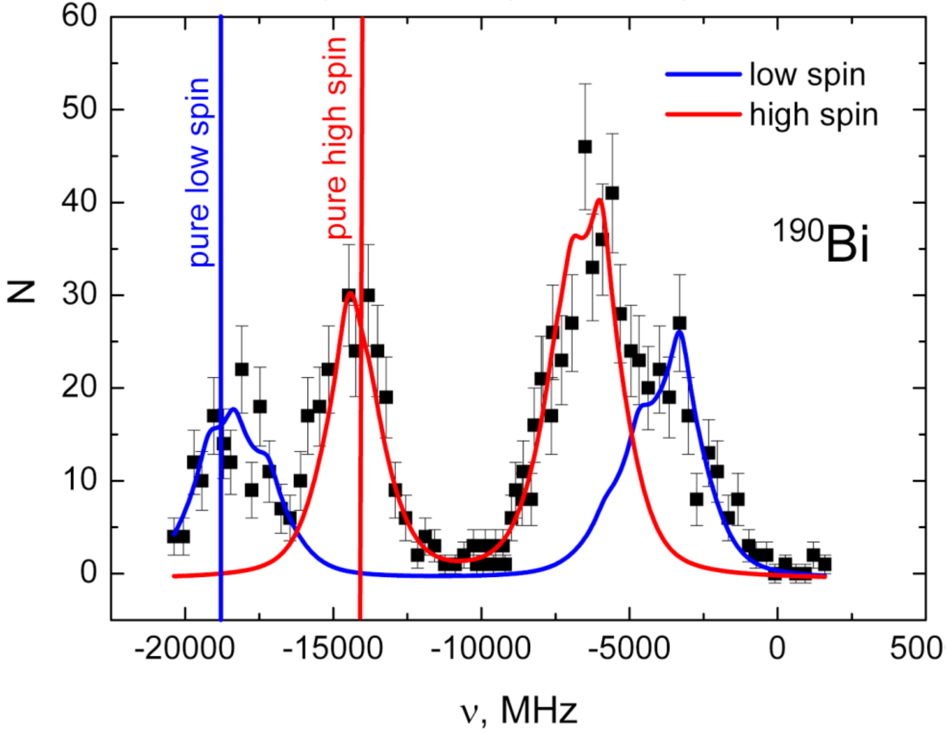
L. Ghys, A.N. Andreyev et al., PRC **90**, 041301(R) (2014)



βDF of $^{186.188}$Bi: SHIP(GSI). J.F.W. Lane, A.N. Andreyev et al., PRC **87**, 014318 (2013) – identification, but no FFs mass measurement, no $P_{\beta DF}$

Isomer separation in ^{190m1,m2}Bi (IRIS@PNPI, Gatchina)

Courtesy A.Barzakh (IRIS@PNPI)



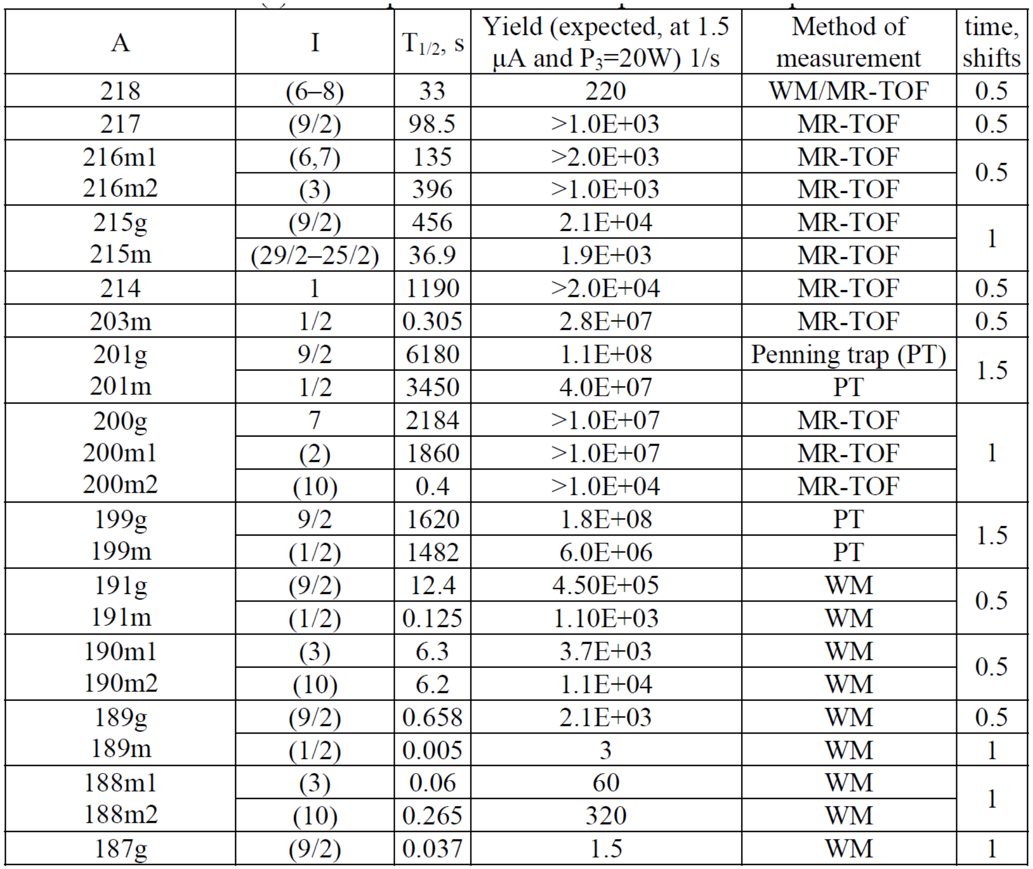
Based on expected similarity of configurations in ^{188m1,m2}Bi and in ^{190m1,m2}Bi, isomerically-pure beams of ^{188m1,m2}Bi should be obtained for βDF study

Table 2. Expected numbers of fission events for βDF of ^{188m1,m2}Bi

	Y, 1/s	α count, 1/s	N_{ff}/N_{alpha} [19]	N_{ff}, 1/h	coincidence events, 1/day
^{188m1}Bi (I=3)	6.00E+01	3.5E+01	2.66E-05	3.4	30
^{188m2}Bi (I=10)	3.20E+02	1.9E+02	4.00E-05	26	220

16 Shifts Requested for βDF measurements of ^{188}Bi at ISOLDE
Measurements to be performed with the Windmill setup

Total beam request



A	I	$T_{1/2}$, s	Yield (expected, at 1.5 μA and P_3=20W) 1/s	Method of measurement	time, shifts
218	(6–8)	33	220	WM/MR-TOF	0.5
217	(9/2)	98.5	>1.0E+03	MR-TOF	0.5
216m1	(6,7)	135	>2.0E+03	MR-TOF	0.5
216m2	(3)	396	>1.0E+03	MR-TOF	
215g	(9/2)	456	2.1E+04	MR-TOF	1
215m	(29/2–25/2)	36.9	1.9E+03	MR-TOF	
214	1	1190	>2.0E+04	MR-TOF	0.5
203m	1/2	0.305	2.8E+07	MR-TOF	0.5
201g	9/2	6180	1.1E+08	Penning trap (PT)	1.5
201m	1/2	3450	4.0E+07	PT	
200g	7	2184	>1.0E+07	MR-TOF	1
200m1	(2)	1860	>1.0E+07	MR-TOF	
200m2	(10)	0.4	>1.0E+04	MR-TOF	
199g	9/2	1620	1.8E+08	PT	1.5
199m	(1/2)	1482	6.0E+06	PT	
191g	(9/2)	12.4	4.50E+05	WM	0.5
191m	(1/2)	0.125	1.10E+03	WM	
190m1	(3)	6.3	3.7E+03	WM	0.5
190m2	(10)	6.2	1.1E+04	WM	
189g	(9/2)	0.658	2.1E+03	WM	0.5
189m	(1/2)	0.005	3	WM	1
188m1	(3)	0.06	60	WM	1
188m2	(10)	0.265	320	WM	
187g	(9/2)	0.037	1.5	WM	1

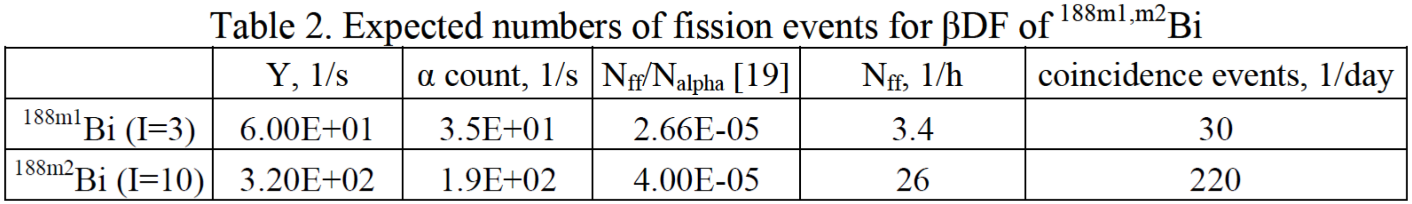


Table 2. Expected numbers of fission events for βDF of ^{188m1,m2}Bi

	Y, 1/s	α count, 1/s	N_{ff}/N_{alpha} [19]	N_{ff}, 1/h	coincidence events, 1/day
^{188m1}Bi (I=3)	6.00E+01	3.5E+01	2.66E-05	3.4	30
^{188m2}Bi (I=10)	3.20E+02	1.9E+02	4.00E-05	26	220

In total, 29 Shifts Requested for HFS/IS studies and βDF measurements of ^{188}Bi

Safety Issues

1. Problems with Tl (Ra) contaminants.

Thallium yields in ISOLDE Database were measured with RILIS. In proposed experiment, Tl will be produced by surface ionization only (thus, at least a factor of 20 lower – a measured factor). Therefore we expect the yields of $^{187-191}$Tl to be equal to ~1÷4·10^{6} 1/s, rather than >10^{7} 1/s. In this mass region WINDMILL will be used for the alpha-particles counting. Only ^{187}Tl has alpha decay branch and its alpha-branching is rather low (0.15%) to produce some background problems for alpha-detection. Thallium contaminants on these masses may force us to switch off gamma detection to avoid dead time in the registration system. But this will not affect the main goal of the measurements — hfs-spectra receiving by alpha-particles detection.

At the same time in the mass region A=199-203 where MR-TOF MS will be used for photo-ion current monitoring, Tl yields are order of magnitude less than Bi yields, and therefore Tl contaminants will not affect our measurements. The problems may arise only for ^{200m}Bi (I=10, $T_{1/2}$=0.4s) where expected Bi yield (>10^{4}1/s) may be comparable or even less than Tl yield (1÷2·10^{5} 1/s). In this case the ion counting behind the Penning Trap can be used (as it is proposed for A=201), where we will benefit from the higher mass resolving power.

The same procedure may be applied for ^{214}Bi also, where big contaminant yield (^{214}Ra) is expected.

It should be stressed that we can substantially reduce the surface ionization efficiency (thus, the contaminants yields) by decreasing the line temperature. It was shown in our previous RILIS experiments that surface ionization decrease much more rapidly with the decrease of the line temperature than the laser ionization.

2. Description of the method of the yield estimation for short lived isomers/isotopes.

^{189m}Bi.
Isomer ratio for A=189 is supposed to be equal to that for A=191 with additional reduction due to different $T_{1/2}$ for g.s. and m.s. at A=189. This reduction factor $R(T_{1/2})$ is calculated conservatively as:
$R(T_{1/2})= \{[T_{1/2}.(^{189m}\mathrm{Bi})/\ T_{1/2}{}^{.(189g}\mathrm{Bi})]/[T_{1/2}.(^{191m}\mathrm{Bi})/\ T_{1/2}{}^{.(191g}\mathrm{Bi})]\}^{3/2} = 0.65$
(in diffusion-effusion model yields behave as $T_{1/2}{}^{3/2}$ at $T_{1/2} << (t_{diffusion}, t_{effusion})$. When this inequality is not valid the dependence of the yield on $T_{1/2}$ is more flat; see: A.E. Barzakh, et al., Eur. Phys. J. **A47**, 70 (2011)).

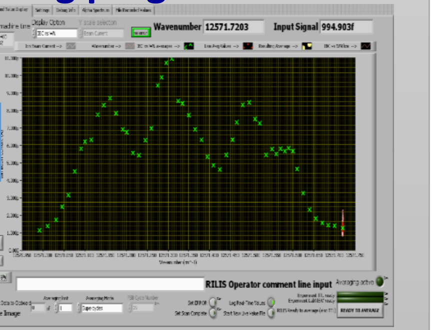
^{187}Bi.
Yield for ^{187}Bi is estimated with the following assumptions:
$Y(^{187}\mathrm{Bi}) = Y(^{188}\mathrm{Bi})*[\sigma(p_{1.4GeV}+^{238}\mathrm{U},\ ^{187}\mathrm{Bi})/\sigma(p_{1.4GeV}+^{238}\mathrm{U},\ ^{188}\mathrm{Bi})]*R(T_{1/2})$
$\sigma(p_{1.4GeV}+^{238}\mathrm{U},\ ^{187}\mathrm{Bi})/\sigma(p_{1.4GeV}+^{238}\mathrm{U},\ ^{188}\mathrm{Bi}) = 0.1$
$R(T_{1/2})= [T_{1/2}.(^{187}\mathrm{Bi})/\ T_{1/2}{}^{.(188}\mathrm{Bi})]^{3/2} = 0.05.$
Note, that $\sigma(p_{1GeV}+^{238}\mathrm{U},\ ^{192}\mathrm{Bi})/\sigma(p_{1GeV}+^{238}\mathrm{U},\ ^{191}\mathrm{Bi}) = 5$, $\sigma(p_{1GeV}+^{238}\mathrm{U},\ ^{191}\mathrm{Bi})/\sigma(p_{1GeV}+^{238}\mathrm{U},\ ^{190}\mathrm{Bi}) = 6$ (J. Taieb, et al., Nucl. Phys. **A 724**, 413 (2003)) and it was shown that at the proton energy 1.4GeV the decrease of the cross-section with the decrease of N at the neutron deficient side is markedly slower than at 1GeV proton energy (U. Georg, et al., Nucl. Phys. **A 701**, 137c (2002)). So, our estimation of the cross-section reduction when going from A=188 to A=187 (10 times) is conservative.
The similar procedure was used in some other cases.

3. Radioprotection issue with long lived contaminants forWINDMILL.
We developed standard procedures to work safely with WM during the last 10 years, and we don't plan to open WM during the run, so no chance for radioactivity release in the experimental hall. In case we need to do it, the usual RP procedures will apply.

Thank you!

Recent technical improvements of the in-source spectroscopy method (2012 onwards)

New live spectra plotting and RILIS DAQ and scanning program



Wavenumber 12571.7203

Input Signal 994.903f

RILIS Operator comment line input

Au

At

Po

General RILIS

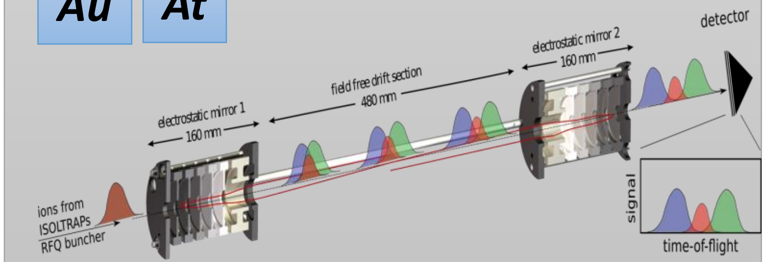
Active beam position stabilization

Dual TiSa and dye laser operation
- 2 spectroscopic transitions
in one experiment

Higher laser power for non-resonant ionization

ISOLTRAP MR-ToF MS ion detection

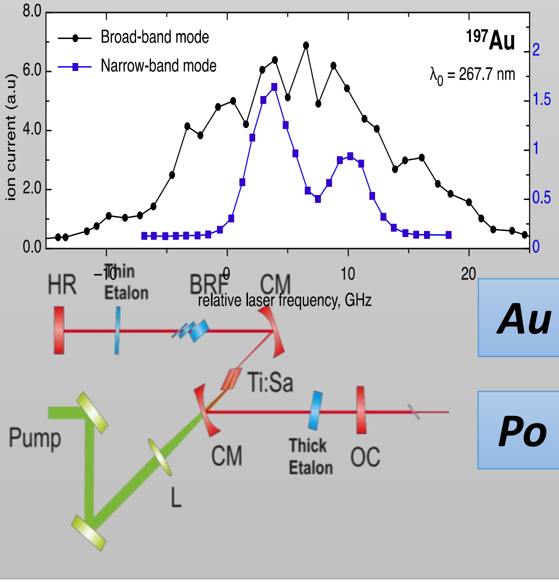
Au **At**



Not limited by decay scheme or long half-lives

Mass resolution in the range of $M/\Delta M = 10^6$

Dual etalon, narrow-band Ti:Sa

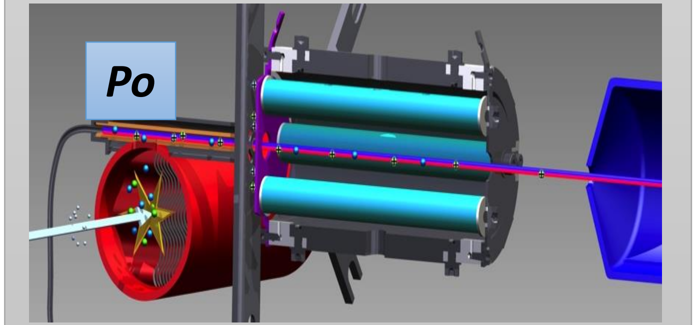


Au

Po

LIST for francium isobar suppression

Po



CURRENT quality factors:

Selectivity improvement = 10^4-10^5

Efficiency loss = 20x

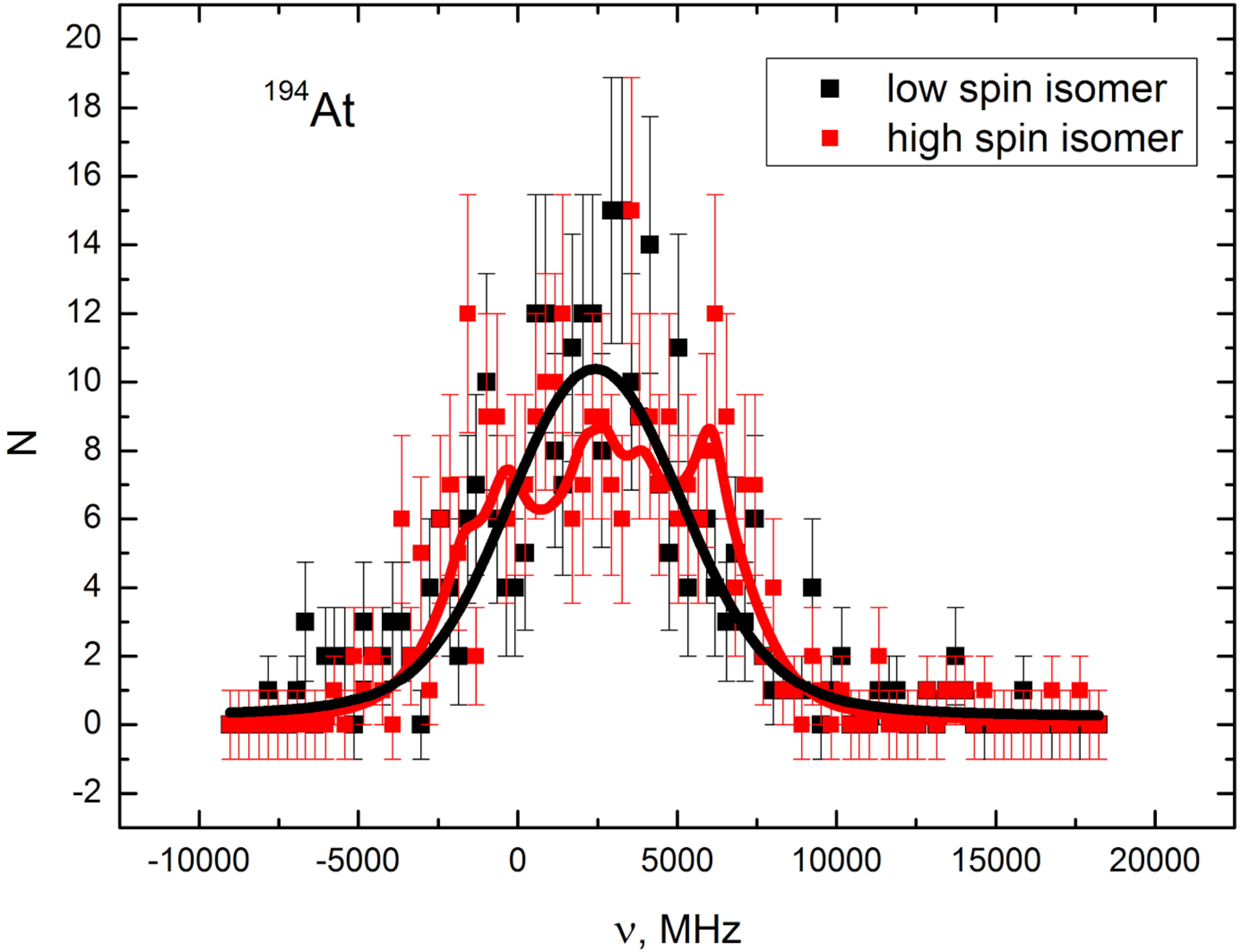
Reference cell for RILIS

Available in 2014

Reference measurements of stable isotopes

slide courtesy B.Marsh

IS534 – An attempt to separate isomers in ^{194}At



Bi's Magnetic Moments (Literature +IRIS)

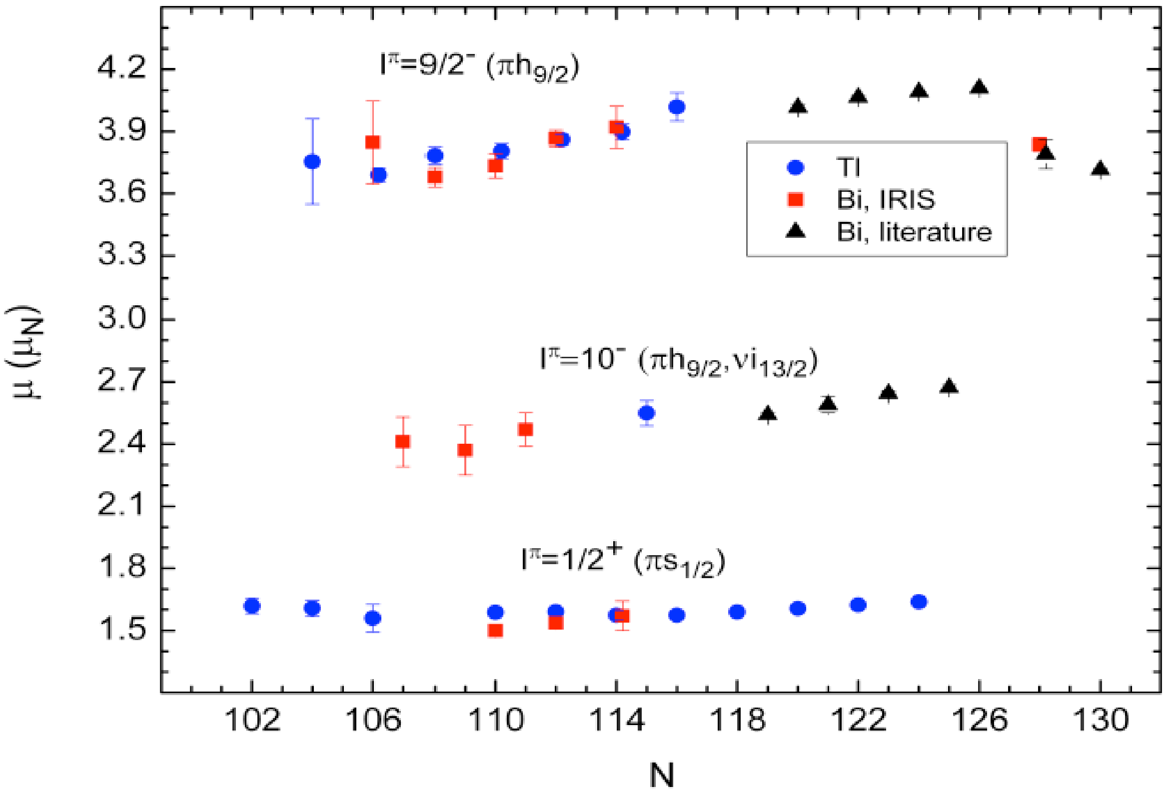
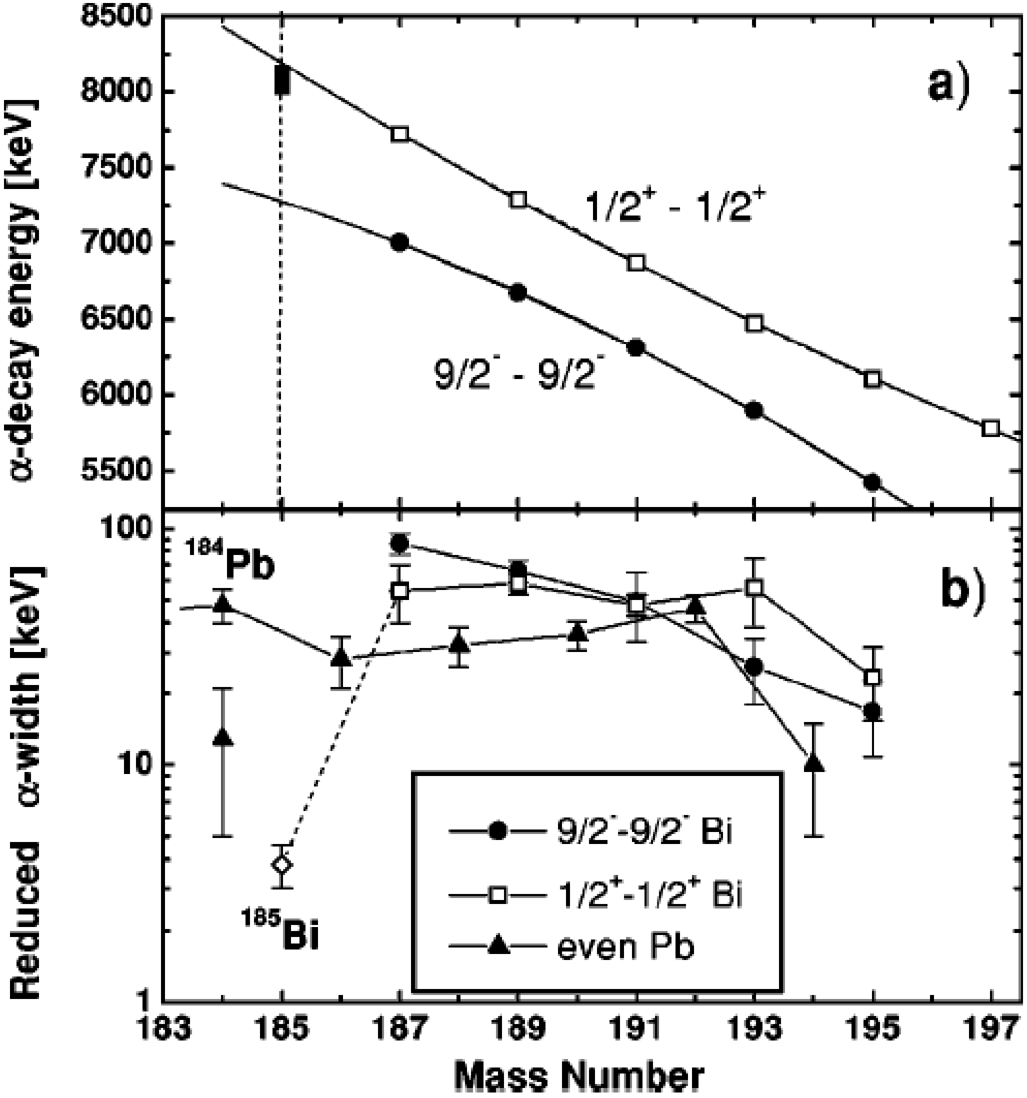
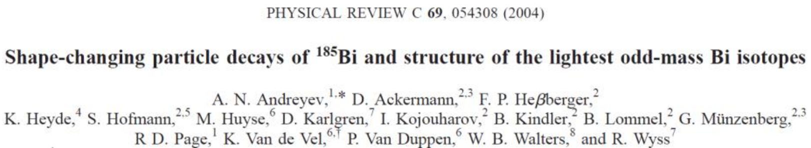


FIGURE 1. (Color online). Magnetic moments for Bi and Tl isotopes and isomers. Squares: Bi, present paper; triangles: Bi, literature data [15]; circles: Tl [6, 15, 16].

AIP Conference proceedings, A. Barzakh et al, (2015)

Bi's Reduced Widths for Alpha decay





PHYSICAL REVIEW C **69**, 054308 (2004)

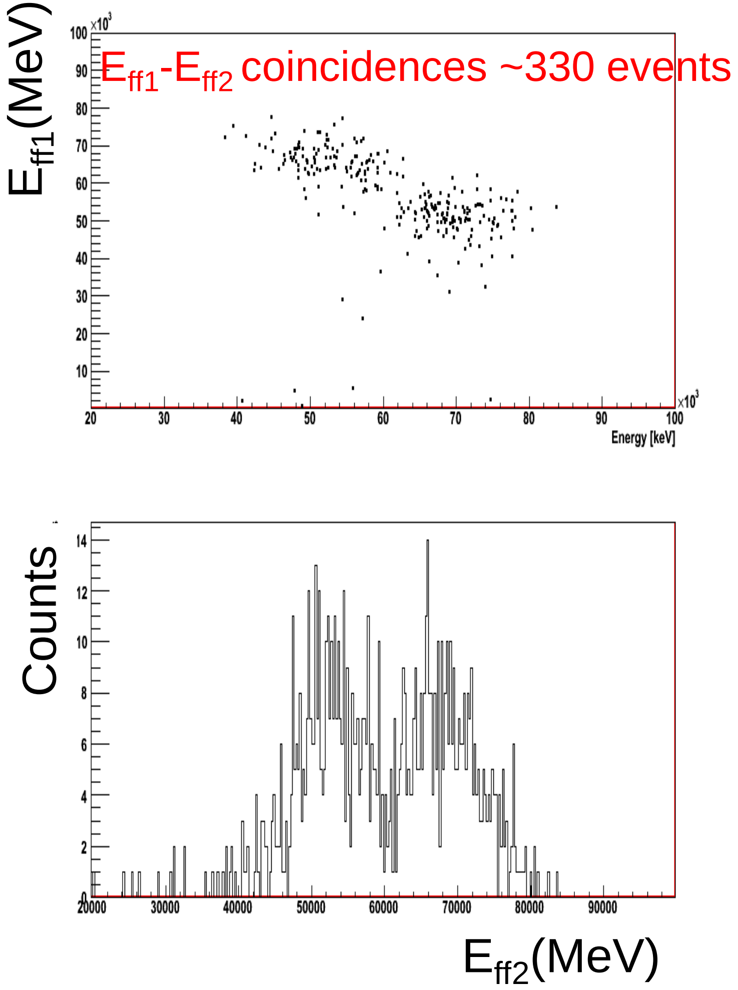
Shape-changing particle decays of ^{185}Bi and structure of the lightest odd-mass Bi isotopes

A. N. Andreyev,[1,*] D. Ackermann,[2,3] F. P. Heβberger,[2]
K. Heyde,[4] S. Hofmann,[2,5] M. Huyse,[6] D. Karlgren,[7] I. Kojouharov,[2] B. Kindler,[2] B. Lommel,[2] G. Münzenberg,[2,3]
R D. Page,[1] K. Van de Vel,[6,†] P. Van Duppen,[6] W. B. Walters,[8] and R. Wyss[7]

Mass distribution of ^{202}Rn via βDF of ^{202}Fr

13-19 May 2011 @ ISOLDE

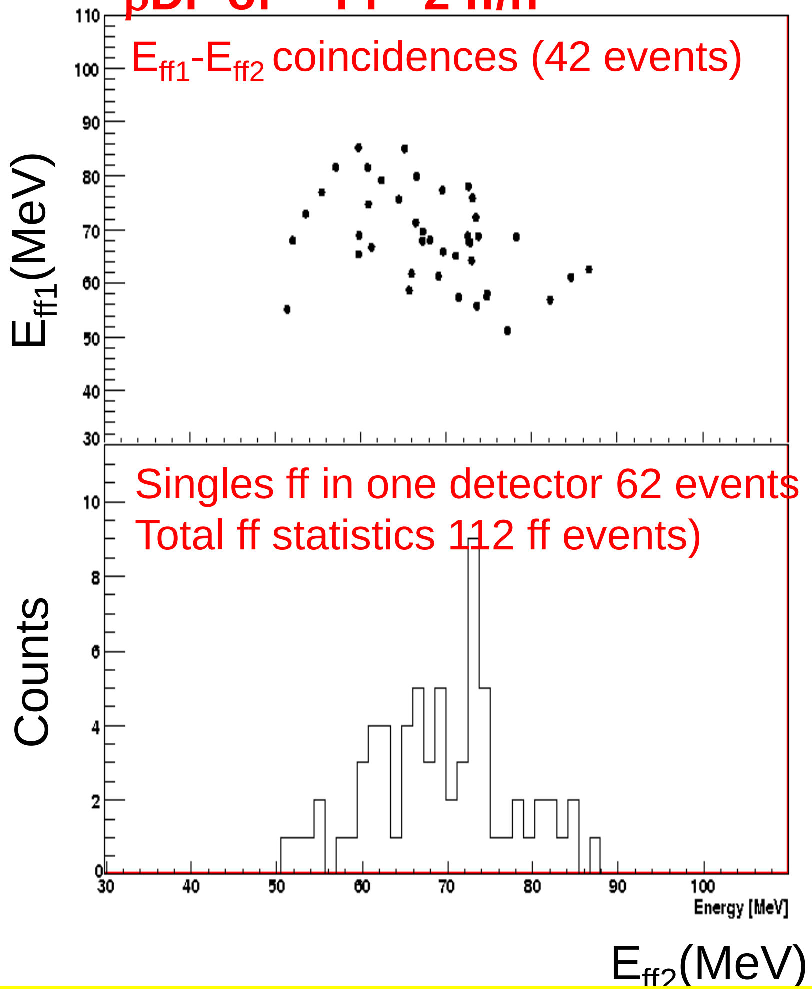
βDF of ^{180}Tl, ~20 ff/h



E_{ff1}-E_{ff2} coincidences ~330 events

^{202}Fr: ~100 ions/s

βDF of ^{202}Fr ~2 ff/h



E_{ff1}-E_{ff2} coincidences (42 events)

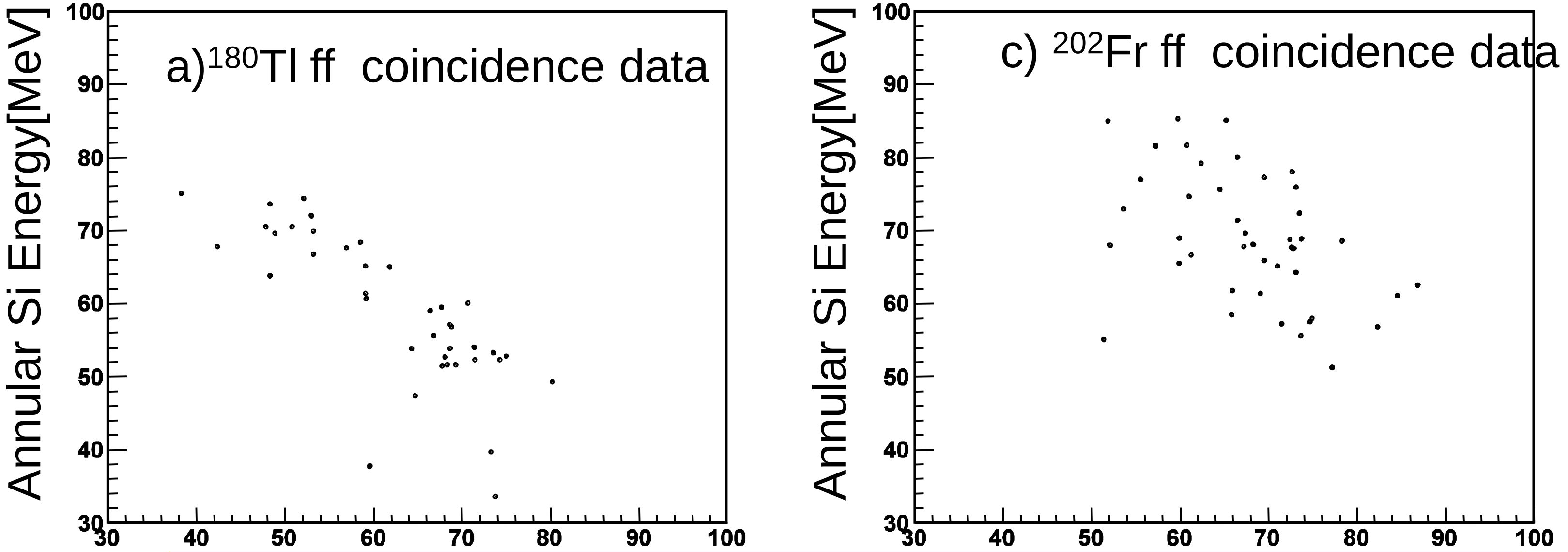
Singles ff in one detector 62 events

Total ff statistics 112 ff events)

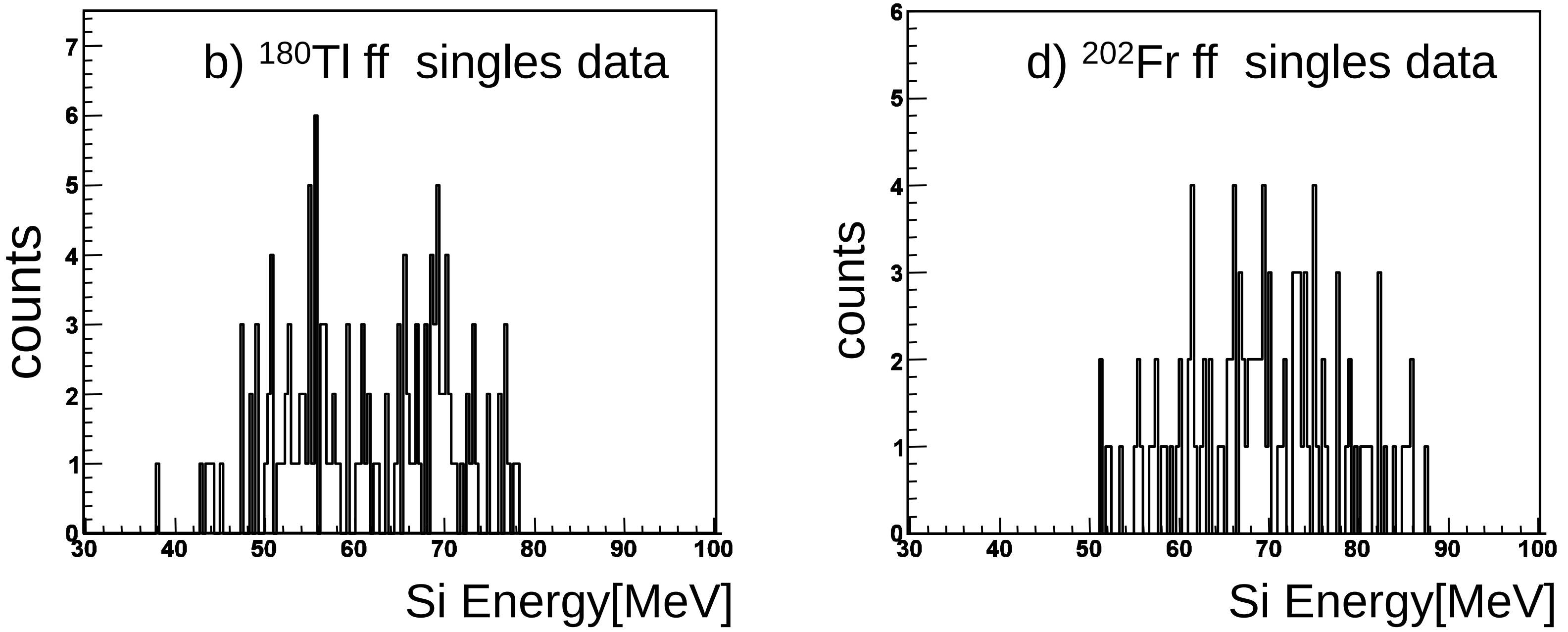
^{178,180}Hg: Asymmetric mass split in nuclei around ^{80}Kr and ^{100}Ru

^{202}Rn: Symmetric mass split in nuclei around ^{100}Mo-^{100}Ru

What can be learned from ~45 coincident ff's?

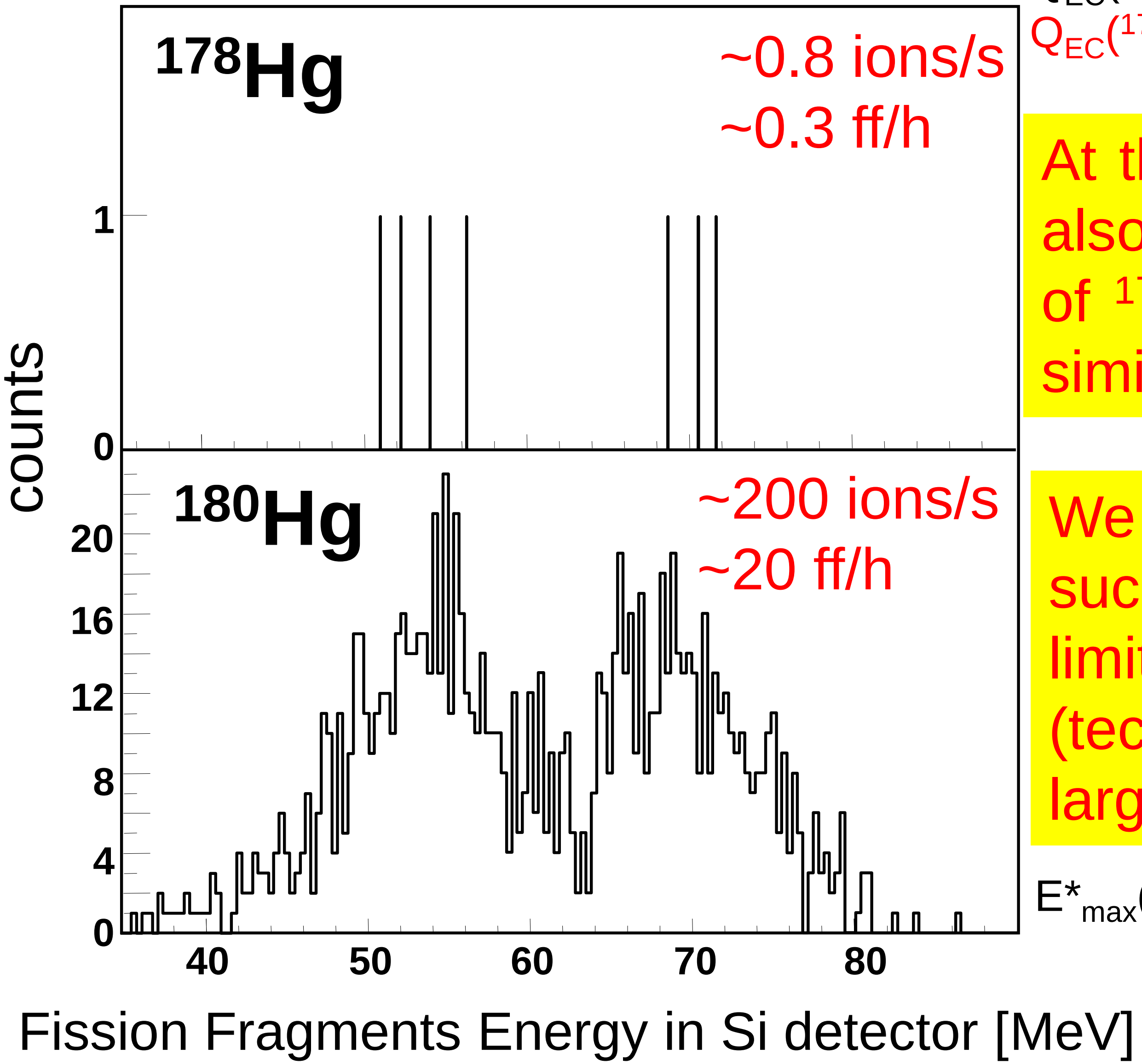


^{180}Hg is **asymmetric**, while ^{202}Rn is **symmetric**



βDF of ^{178}Tl @ISOLDE

V. Liberati et al (draft is ready)



$Q_{EC}(^{178}Tl)=E^*_{max}(^{178}Hg)=11.14$ MeV

$Q_{EC}(^{178}Tl)-B_f(^{178}Hg)=1.82$ MeV

At this level of statistics: also asymmetric fission of ^{178}Hg, with mass split similar to ^{180}Hg

We also tried ^{182}Tl, no success so far, upper limit for $P_{\beta DF}<10^{-6}$ (technically difficult, large β/γ yields)

$E^*_{max}(^{180}Hg)=10.44$ MeV